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STELLARMAK A HYBRID STELLARATOR - SPHEROMAK

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I. Introduction

It has been known for some time that nonaxisymmetric, vacuum-field, toroidal confinement systems can be formed by combination of axisymmetric multipole fields and modified Stellarator-like fields.[1] This "hybridization" can result in improved negative V'' properties and shear. In addition, simpler coil topology, as compared with a conventional Stellarator, is possible since the Stellarator-like windings need not link the torus. Initial calculations were concerned largely with vacuum fields however, it is apparent that plasma current can also serve to provide a poloidal field which can then be transformed in the toroidal direction by helical stellarator windings as has been recently suggested[2].

This paper discusses hybridization of modified Stellarator-like transform windings (T-windings) with a Spheromak[3] or Field-Reversed-Mirror configuration.[4] This configuration-Stellarmak-retains the important topological advantage of the Spheromak or FRM of having no plasma linking conductors or blankets. The T-windings provide rotational transformation in toroidal angle of the outer poloidal field lines, in effect creating a reversed $B_{Toroidal}$ Spheromak or adding average B_T to the FRM producing higher shear, increased limiting β, and possibly greater stability to kinks and tilt. The presence of field ripple in the toroidal direction may be sufficient to inhibit cancellation of directed ion current by electron drag to allow steady state operation with the toroidal as well as poloidal current maintained by neutral beams.

II. Stellarmak Configuration

The basic hybrid approach is shown in Fig. 1. Axisymmetric fields are provided by I_z, the two rings, and a uniform B_z to give the poloidal-field pattern shown. Helical windings, centered on the z-axis, provide Stellarator-like rotational transform. The combined fields give numerically computed toroidal magnetic surfaces as shown with the rotational transform on the small-major-radius side of the surfaces provided by the axisymmetric poloidal field and the transform on the large-major-radius side provided by the helical windings. Continuation of the rotational transform by the axisymmetric B_p eliminates the need for helical windings which link the toroidal surfaces.

Application of T-windings to produce toroidal rotational transform ι_T of the basic poloidal field of a Spheromak is shown in Fig. 2. The modular T-windings shown in Fig. 2(a) lie on a sphere and follow loxodromic spiral trajectories with latitudinal cross-links. A vacuum poloidal field line near $\psi = 0$ passes near the axis of the Spheromak, emerges at the poles, and returns near the spherical surface where the T-windings induce toroidal transform modifying the basic Spheromak configuration to that shown in Fig. 2(b). Numerical calculations in progress (assuming vacuum B_p) have given t_T/t_p = .04 for 8 T-winding modules with flux surfaces as shown in Fig. 2(c). Alternatively T-windings for a highly prolate reversed-field- configuration would more nearly resemble the helices of Fig. 1 and arbitrarily large t_T/t_p could be obtained depending on the elongation.

III. MHD Stability Aspects

The most striking aspect of introducing transform windings to a Spheromak/FRM is that shear and reversed toroidal transform can be introduced externally without hole-linking conductors. For a large aspect ratio stabilized Z-pinch the maximum stable β is increased from 15% to 40% in going from a field profile having $B_T = 0$ on the last ψ_P surface to the usual reversed B_T configuration. A similar factor of 3 in β can possibly be obtained for the Stellarmak providing ballooning limits are not encountered. Similarly, T-windings added to the FRM can lend shear stabilization to an otherwise MHD unstable configuration.

Since a conventional stellarator is stable to tilt and slip solid body motions, the transform windings would presumably give improved stability in the Stellarmak.

IV. Equilibrium Aspects

Probably the most significant advantage to be gained by introducing symmetry perturbing transform windings is the potential of sustaining the plasma currents by injection of directed neutral beams. Electron trapping and viscous effects caused by the field ripple can prevent electron cancellation of the ion directed current opening the way to a truly steady state system. For a large spheromak reactor with resistively decaying currents the Q based on resistive losses is,[3]

$$Q_M = \int P_F \, dt/W_M \simeq 100 \sim \beta^2 B^2$$

so that a relatively small current-sustaining beam power is necessary if the process is fairly efficient. This is especially true if βB is increased by a factor of 3 by enhanced stability.

References

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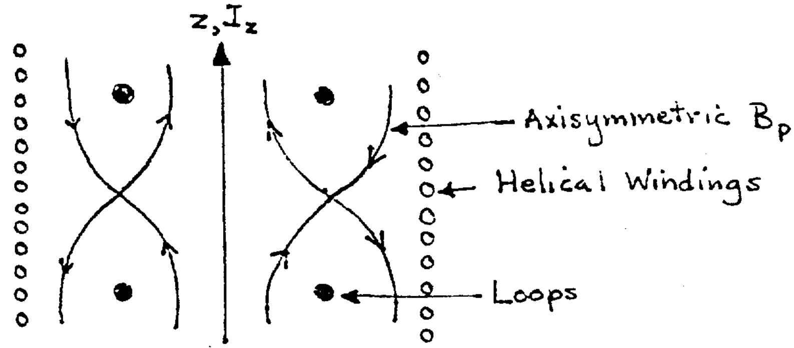
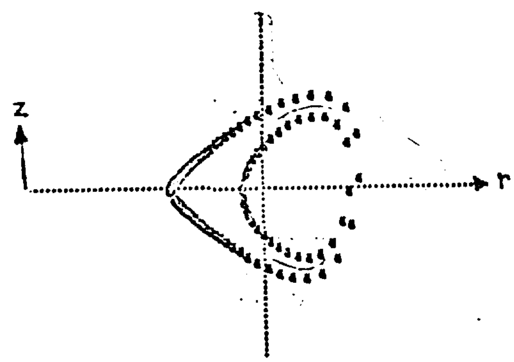


(a) Coil Configuration



(b) Magnetic Surfaces

Fig. 1. Hybritron Configuration. Intersections of magnetic surfaces with the r-z plane [Fig. 2(b)] were computed for the coil configuration [Fig. 2(a)] with $B_T = 1/r$, $B_{zo} = 0.12$, $I_{Loops} = -0.12$ (at $r = 1$, $z = \pm 1$) and with a helical magnetic potential $\chi = C_\lambda I(kr) \cos(\lambda\phi + kz)$ where $\lambda = 6 = k$ and $C_\lambda = 1$.

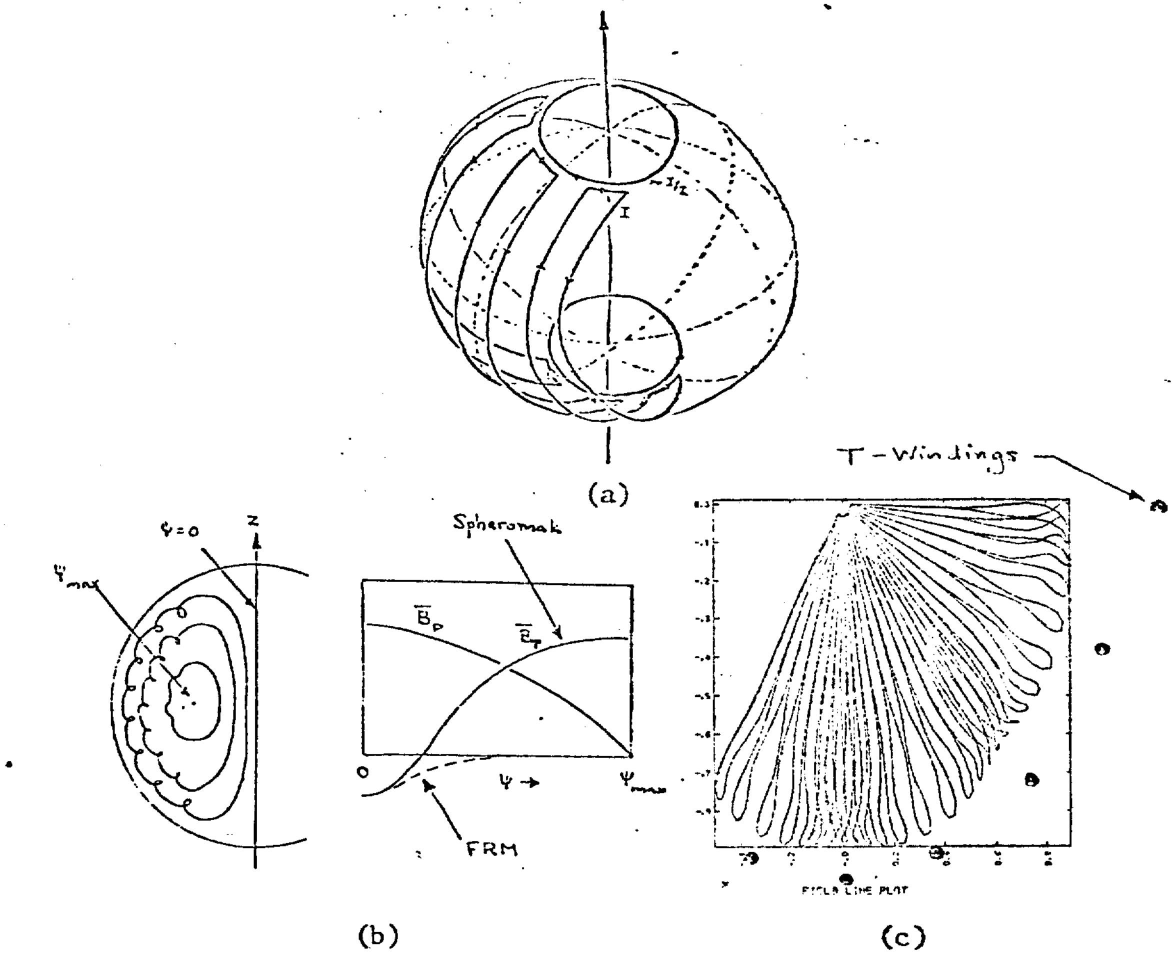


Fig. 2. Stellarmak Properties. Fig. 2(a) shows three modular T-windings based on loxodromic spirals and latitudinal cross-links. Also shown are compensating loops. Fig. 2(b) shows heuristic field-line-trajectory projections in a meridinal plane. Also shown are average $\overline{B}_P$ and $\overline{B}_T$ vs ψ for Spheromak and FRM configurations. Fig. 2(c) shows computed field-line projections in the equatorial plane for 8 modular windings.